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Regional and Local Stratigraphy of Uranium-Bearing Rocks

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INTRODUCTION

The Grants uranium region encompasses the two most productive sedimentary uranium mining districts in the state, Ambrosia Lake in the west, and Laguna in the east. U.S. Highway 66 extends northwesterly through the southern part of the area and the principal towns, Grants and Laguna, are on the highway in the western and eastern parts, respectively.

This paper presents the regional stratigraphy of the uranium-bearing rocks in the Grants region and the stratigraphic relations between the Grants and Laguna districts.

GEOLOGIC SETTING

The Grants uranium belt is flanked on the north-northeast by the San Juan Basin, on the east by the Rio Grande trough, and on the south and west by the Acoma sag and the Zuni uplift (Kelley, this memoir, fig. 1; Laverty et al., this memoir, fig. 1). The sedimentary rocks exposed in the area range in age from Pennsylvanian to Cretaceous and rest on the Precambrian core of the Zuni uplift. Associated intrusive and extrusive rocks of the Mount Taylor and Zuni volcanic fields are of Tertiary and Quaternary ages. Regional dip of the sedimentary rocks is generally northward toward the San Juan Basin, but it arcs from northeastward in the Grants district to northwestward in the Laguna district. This regional attitude is modified locally by normal faults and minor folds.

STRATIGRAPHY

Of the sedimentary rocks that are exposed in the area, mineable uranium deposits are found only in those of Jurassic and Cretaceous ages. These rocks are, in ascending order, the Entrada Sandstone, Todilto Limestone, Summerville Formation, and Bluff Sandstone of the San Rafael Group, and the Morrison Formation, all of Late Jurassic age; and the Dakota Sandstone, of Early and Late Cretaceous age (table 1). This sequence is about 1000 to 1500 feet thick and rests on either the Wingate Sandstone of the Glen Canyon Group or on the Chinle Formation, both of Late Triassic age. The Morrison Formation and Todilto Limestone are described and discussed in greater detail because they have yielded nearly all the ore and probably contain more than 95 percent of the reserves.

ENTRADA SANDSTONE

NOMENCLATURE AND REGIONAL RELATIONS

The Entrada Sandstone is the lowermost uranium-bearing unit and the basal formation of the San Rafael Group in the Grants region. The formation was named from exposures in the northern end of the San Rafael Swell, Utah (Gilluly and Reeside, 1928). Later it was found to extend into northwestern New Mexico (Baker, Dane, and Reeside, 1936, p. 7-8, fig. 12) and, subsequently, was recognized by the U.S. Geological Survey throughout most of the San Juan Basin area when it was supposed that the upper part of the thick cliff-forming sandstone north of Fort Wingate, called the Wingate Sandstone by Dutton (1885), could be correlated with the type section of the Entrada and with widespread exposures of the unit in Utah, Colorado, and northern New Mexico (Baker, Dane, and Reeside, 1947). The name *Entrada Sandstone* was therefore extended by the Survey to include the upper thick sandstone at the type locality of the Wingate Sandstone and the name *Wingate* was shifted to the sandstone below a medial silty unit, with the edict that the original type locality of the Wingate be abandoned (Baker, Dane, and Reeside, 1947, p. 1667-1668).

The silty unit at the base of the Entrada was formerly considered correlative with the Carmel Formation, the lowermost formation of the San Rafael Group (Baker, Dane, and Reeside, 1947). Later work, however, indicated that the Carmel probably extends eastward from Arizona and Utah only to the proximity of New Mexico (Wright and Dickey, 1958, p. 174-175). The silty unit at Fort Wingate is accordingly thought to be correlative with the medial silty member of the Entrada in northeastern Arizona (Strobell, 1956; Harshbarger, Repenning, and Irwin, 1957, p. 35).

The Entrada is the most extensive unit of the San Rafael Group. From a feather edge in central Colorado, it thickens westward to a maximum thickness of nearly 2000 feet in central Utah and extends southward into northeastern Arizona, northwestern New Mexico, and northward into southwestern Wyoming. It is concordant on the Carmel in eastern Utah and northeastern Arizona and to the east beyond the limit of the Carmel is unconformable on older rocks (Wright and Dickey, p. 172-177).

The Entrada on the Colorado Plateau generally includes two distinct lithologic types. The first is a reddish orange to light gray, well-sorted, quartz sandstone that is conspicuous by sweeping large-scale cross-strata. It forms the entire thickness in most of Colorado but, to the west, interfingers with the second lithologic type, a red, earthy siltstone, which in turn forms the entire thickness of the formation near the western edge of the San Rafael Swell (Wright and Dickey). This siltstone is poorly sorted and weathers into grotesque erosion forms locally referred to as *hoodoos*.

In northeastern Arizona, adjacent parts of Utah, and northwestern New Mexico, Harshbarger, Repenning, and Irwin (p. 35-38) recognized three members—a lower sandy member that is present only in Arizona and Utah, a medial silty member, and an upper sandy member. The medial silty member and upper sandy member, as established at Fort Wingate, have been extended eastward into the Laguna district (Harshbarger, Repenning, and Irwin; Smith, 1954; Rapaport, Hadfield, and Olson, 1952) and generally extend northeastward from Laguna into north-central New Mexico (D. D. Dickey, written communication, 1963).

In most places, the Entrada rests on the Upper Triassic Wingate Sandstone (Harshbarger, Repenning, and Irwin, p. 8, 11), but at least in the southeastern part of the Laguna district (where the Wingate undoubtedly is missing), it rests on the Chinle Formation (Kelley and Wood, 1946; Silver, 1948; Rapaport, Hadfield, and Olson; Harshbarger, Repenning, and Irwin). Elsewhere in the Laguna district, rocks previously called Wingate might belong in the Entrada. If so, the Entrada rests on the Chinle throughout the district. This problem is discussed below under local relations.

The Entrada Sandstone probably comprises marine, fresh-water, and eolian deposits. In central Utah where it grades into the Carmel Formation it probably represents marine deposits, although fossil evidence is lacking. Eastward, these beds appear to grade into fluvial, lacustrine, and eolian deposits. In the southeastern part of the area, including northwestern New Mexico, the silty member of the Entrada probably largely represents fresh-water and possibly some marine

Table 1. *Sequence of stratigraphic units containing uranium deposits in the Ambrosia Lake-Laguna area, New Mexico.*

System	Age	Formation	Thickness (feet)	Character and distribution	Uranium deposits
Cretaceous	Early and Late Cretaceous	Dakota Sandstone	<5-125	Tan to gray, medium-grained quartz sandstone, some interbedded carbonaceous shale and local coal lenses. Local conglomerate-filled scours at base as much as 25 feet deep.	Scattered small deposits, generally near base and closely related to carbonaceous material. A few in Ambrosia Lake district have yielded ore.
		Unconformity			
Jurassic	Late Jurassic	Morrison Formation	0-600	Brushy Basin Member: mostly greenish-gray mudstone and local thick arkosic sandstone units. Contains Poison Canyon sandstone of economic usage near base in Ambrosia Lake district and Jackpile sandstone of economic usage at top in Laguna district. Member is 20-300 feet thick and generally thickens eastward and northward from Ambrosia Lake district.	Sandstone lenses contain many deposits. Very large deposits occur in Jackpile sandstone in Laguna district and large ones occur in Poison Canyon sandstone and other sandstone units in Ambrosia Lake district.
				Westwater Canyon Member: light-brown to gray, poorly sorted, arkosic sandstone and some interbedded gray mudstone. Intertongues with Brushy Basin Member and thins from maximum of about 300 feet in Ambrosia Lake district to less than 50 feet in the Laguna district where locally absent.	Contains many large deposits in Ambrosia Lake district.
				Recapture Member: distinctive alternating beds of gray sandstone and grayish-red siltstone or mudstone. Beds are a foot to several feet thick. Contact with Bluff Sandstone generally sharp, but intertongues with Westwater Canyon Member. Recapture is less than 50 to more than 200 feet thick.	Contains a few small deposits. One in Laguna district has yielded ore.
		Bluff Sandstone	150-400	Pale-red to pale-brown, fine- to medium-grained sandstone. Forms massive cliffs. Upper part marked by thick sets of large-scale crossbeds; lower part grades down into smaller-scale sets of crossbeds and some flat beds.	Contains no deposits.
		Summerville Formation	90-200	Alternate beds of pale-brown, thin-bedded sandstone and reddish-brown mudstone or siltstone. Sandstone beds thicken in upper part and grade into overlying Bluff Sandstone; at base grades and intertongues with Todilto.	Contains scattered deposits at base, generally where underlying Todilto Limestone is mineralized.
		Todilto Limestone	0- 85	Consists of upper gypsum-anhydrite member, exposed only in Laguna district, 0-75 feet thick; and lower limestone member, gray, laminated in lower part and more massive, contains interbedded siltstone in upper part, 5-35 feet thick.	Contains (mostly in Ambrosia Lake district) many small and some fairly large deposits in the limestone member.
		Entrada Sandstone	150-250	Consists of upper unit, 80-250 feet thick, of reddish-orange, fine-grained sandstone with thick sets of large-scale crossbeds and a medial unit, 10-85 feet thick, of red and gray siltstone. In the Laguna district, a lower sandstone unit, 0-30 feet thick, may belong in the Entrada or may be the Wingate Sandstone. Medial unit probably unconformable on Wingate Sandstone in Ambrosia Lake district; lower sandstone unit unconformable on Chinle Formation in Laguna district.	Contains scattered small deposits at top of formation, generally where overlying Todilto Limestone is mineralized. Some have yielded ore.
		Unconformity			
Triassic	Late Triassic	Wingate Sandstone and Chinle Formation		Not described.	

deposits, and the sandy members probably largely represent eolian and some fluvial beds. These features are discussed by Gilluly and Reeside, Baker, Dane, and Reeside (1936), Imlay (1952), Harshbarger, Repenning, and Irwin, and Wright and Dickey.

The Entrada is assigned to the Late Jurassic because of its gradational relations with the Carmel Formation and its stratigraphic position below the Curtis Formation, both of which contain Late Jurassic marine fossils (Gilluly and Reeside, p. 76-79; Baker, Dane, and Reeside, 1936, p. 7-8; Imlay, p. 962).

LOCAL RELATIONS

In the Ambrosia Lake area, the Entrada crops out north of U.S. Highway 66 and, south of Grants, it is partly exposed in several places along State Highway 117 to a point about 20 miles south of U.S. Highway 66. Approximately from Grants to Laguna, a distance of about 30 miles, the Entrada is covered. In the southern and eastern parts of the Laguna district, the Entrada is well exposed along U.S. Highway 66. The southernmost exposure is about 25 miles south of Laguna.

In the Grants region, the medial silty member is about 10 to 85 feet thick and consists of thin-bedded, red and gray, friable siltstone and fine-grained quartzose sandstone. It grades and interfingers into the upper sandy member, which is 80 to 250 feet thick. The upper sandy member is a reddish orange to light gray, moderately well-cemented and well-sorted, fine- to medium-grained quartz sandstone. It tends to crop out in a prominent rounded cliff or "slick rim," the upper part of which is generally bleached to light gray. The upper sandy member is marked by thick sets of large-scale, planar cross beds, but contains less conspicuous, relatively thin, flat-bedded sets.

Locally in the Laguna district, a sandstone unit lithologically and structurally similar to the upper sandy member of the Entrada occurs at the base of the silty member. According to Silver, this sandstone is the Wingate. Silver, who apparently accepted Dutton's type section at Fort Wingate and referred all the beds between the Chinle and Todilto to the Wingate, indicated in a footnote (p. 74) that his units are equivalent to the revised nomenclature of Baker, Dane, and Reeside (1947). Thus, as shown in Table 2, Silver's lower cliff-forming member is the Wingate Sandstone of Baker, Dane, and Reeside (1947) and Harshbarger, Repenning, and Irwin; Silver's middle slope-forming member is equivalent to the Carmel of Baker, Dane, and Reeside (1947) and to the medial silty member of the Entrada of Harshbarger, Repenning, and Irwin; and Silver's cliff-forming member is equivalent to the Entrada of Baker, Dane, and Reeside (1947) and to the upper sandy member of the Entrada of Harshbarger, Repenning, and Irwin. R. H. Moench, however, who has mapped the Laguna district in detail, includes all of Silver's original Wingate in the Entrada, principally for lack of evidence of erosion under Silver's middle slope-forming member and for the lithologic and structural similarity to the lower and upper cliff-forming members of Silver (R. H. Moench, written communication, 1963).

The lower sandstone unit of Moench unconformably overlies the Chinle Formation on Petoch Butte, in the southwest corner of the Laguna district, and is exposed in a line of outcrops that extends eastward about four miles from the western margin of the district. To the east, the middle siltstone unit of Moench rests on the Chinle, small discontinuous lenses of the lower sandstone unit being exposed only locally. The lower sandstone unit thins from about 30 feet thick at Petoch Butte to a knife edge about six miles to the northeast, and it tends to coarsen southward and downward. Deep scours at the base contain coarse-grained sandstone and locally quartz-pebble conglomerate, and the contact with the overlying siltstone unit is flat and sharp (R. H. Moench, written communication, 1963). Correlation of the Entrada Sandstone units in the Laguna district with the units in the Ambrosia Lake area requires some understanding of the stratigraphic relations of the Wingate Sandstone, which are reviewed briefly.

The Wingate Sandstone is about 350 feet thick at Fort

Table 2. *Nomenclature of the Entrada Sandstone along the south side of the San Juan Basin.*

Harshbarger, Repenning, and Irwin, 1957 (Fort Wingate area)		Baker, Dane, and Reeside, 1947 (Fort Wingate) Rapaport, Hadfield, and Olson, 1952 (South side San Juan Basin)	C. T. Smith, 1954 (Thoreau quadrangle)		Caswell Silver, 1948 (Jurassic overlap, west-central New Mexico)		R. H. Moench, written communication, 1963 (Laguna district)	
Entrada sandstone	Upper sandy member	Entrada sandstone	Entrada sandstone	Upper member	Wingate sandstone	Upper cliff-forming member	Entrada Sandstone	Upper sandstone unit
	Medial silty member	Carmel formation		Lower member		Middle slope-forming member		Middle siltstone unit
Wingate sandstone		Wingate sandstone	Wingate(?) formation			Lower cliff-forming member		Lower sandstone unit

Wingate. It thins eastward to less than 100 feet in thickness in the Thoreau quadrangle (Harshbarger, Repenning, and Irwin, p. 11; Smith, 1954) and to about 50 feet north of Grants. In this general area, the Wingate rests on the Chinle Formation and is overlain by the Entrada Sandstone. Both contacts are erosional surfaces but without marked angularity between the beds on either side (Harshbarger, Repenning, and Irwin, p. 11; Smith, 1954; Rapaport, Hadfield, and Olson). The upper contact with the Entrada Sandstone, although not markedly angular, must represent a fairly large time interval because of the respective Late Triassic and Late Jurassic ages of the Wingate and Entrada Sandstones. During this time, some beds at the top of the Wingate probably were removed by erosion prior to deposition of the Entrada. The eastward thinning of the Wingate between Fort Wingate and the Grants area could, therefore, be at least partly a result of such erosion. Correlation of the Wingate and Entrada units in the Ambrosia Lake area with their respective units in the Laguna district is, therefore, dependent partly on the recognition of this erosion surface in the Laguna district.

From the available data, there appear to be two alternative interpretations or correlations. The first interpretation is that the Wingate Sandstone is cut out completely between Ambrosia Lake and Laguna under the erosion surface at the base of the Entrada Sandstone, as shown in Figure 1. If so, the erosion surface on the Wingate in the Ambrosia Lake area is correlative with the erosion surface on the Chinle Formation in the Laguna district. If so, the lower sandstone unit of the Entrada Sandstone of Moench probably grades westward into his middle siltstone unit, which is the correlative of the medial silty member of Harshbarger, Repenning, and Irwin, as shown in Table 2.

The second interpretation is that the erosion surface on the Wingate in the Ambrosia Lake area is correlative with the top of the lower sandstone unit of the Entrada Sandstone of Moench (fig. 1). If so, the lower sandstone unit of Moench is correlative with the Wingate Sandstone of Harshbarger, Repenning, and Irwin, as shown in Table 2. This interpretation requires the acceptance of the lack of erosional features and the conformity of the beds along the contact between the lower sandstone and middle siltstone units of Moench as a somewhat abnormal local condition. A completely acceptable correlation of the Entrada units between the two districts will probably require more complete information.

The Entrada Sandstone contains many uranium deposits in the Ambrosia Lake–Laguna area, but few have yielded ore.

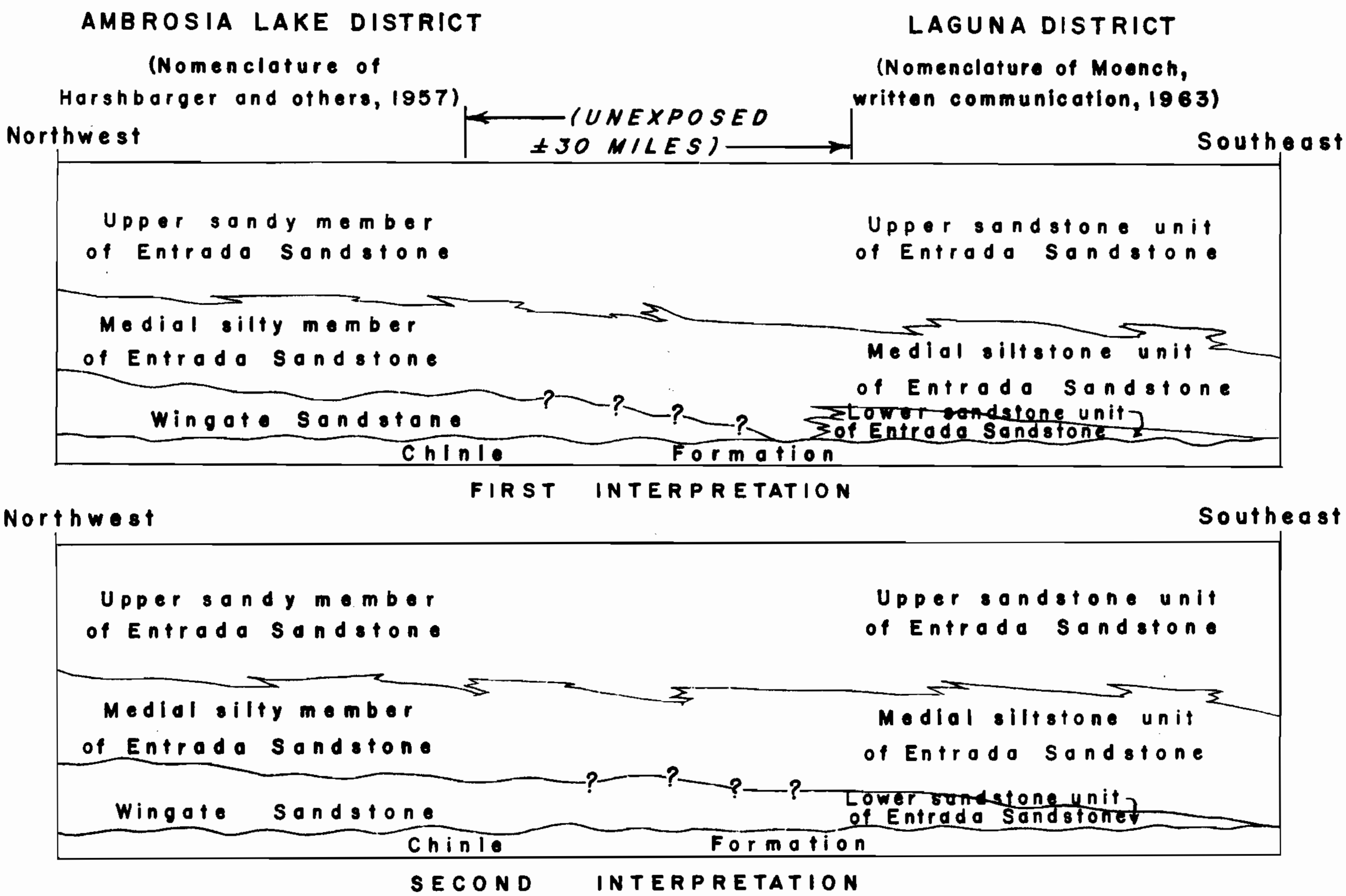

Figure 1

Two interpretive correlations of stratigraphic units of the Entrada Sandstone and the Wingate Sandstone between the Ambrosia Lake and Laguna districts

Most, if not all, the deposits are at the top of the formation and generally represent the basal parts of deposits in the overlying Todilto Limestone. Examples of deposits that have yielded ore are the Sandy, in the Laguna district, and the Zia, in the Grants district.

TODILTO LIMESTONE

NOMENCLATURE AND REGIONAL RELATIONS

The Todilto Limestone, which overlies the Entrada Sandstone in the Grants region, was originally described from a 10-foot-thick exposure of limestone in Todilto Park, New Mexico (Gregory, 1917, p. 55). Baker et al. (1927, p. 803) assigned it as a formation in southeastern Utah, but doubted the equivalence of the beds to the Todilto of eastern Arizona and northwestern New Mexico. The Todilto was assigned as a member and "somewhat incongruous associate" of the Morrison Formation (Baker, Dane, and Reeside, 1936, p. 9) and, still later, was included in the San Rafael Group as a member of the Wanakah Formation of southwestern Colorado (Baker, Dane, and Reeside, 1947, p. 1668). Then, because of its distinctive lithology and wide extent, Northrop (1950, p. 36) and Wright and Becker (1951) raised it to formation rank and included it in the San Rafael Group—a status which has been generally accepted (Smith, 1954, p. 13-14; Harshbarger, Repenning, and Irwin, p. 38-39; Anderson and Kirkland, 1960).

The Todilto Limestone is conformable on and generally gradational with the Entrada Sandstone and is distributed throughout most of northwestern New Mexico, adjacent parts of northeastern Arizona, northeastern New Mexico, and southwestern Colorado (Anderson and Kirkland, p. 44). In the San Juan Mountains, Colorado, its equivalent is referred to as the Pony Express Member of the Wanakah Formation (Read et al., 1949; Imlay, p. 960).

The southern depositional margin of the Todilto is a line 10 to 20 miles south of U.S. Highway 66 that trends westerly to a point south of Grants and then swings northwesterly and into Arizona west of Todilto Park (Rapaport, Hadfield, and Olson).

The Todilto is composed of two members, a basal limestone member, which is from 0 to about 40 feet thick and rather widespread, and an upper gypsum-anhydrite member that is more restricted and up to about 125 feet thick. The basal member consists of thin-bedded and laminated, gray, fine-grained limestone, some thin interbeds of siltstone, and near the top some thin seams of gypsum. In some places, the beds are nearly black, and fine-grained black carbonized material is concentrated along the bedding planes. When pulverized, the limestone emits a fetid odor. This characteristic, coupled with the dark hue, has led many to describe the limestone as "petroliferous." Whether or not the limestone contains hydrocarbons and is petroliferous, its content of organic carbon is low. In 14 bulk samples selected by the writer along the outcrop and from drill holes around the San Juan Basin, the content of organic carbon ranged from 0.20 to 1.6 percent and averaged 0.6 persent (analyses by Irving Frost, U.S. Geological Survey).

The bedding of the limestone member is contorted in many places. Where strongly disturbed, the beds are folded into a variety of shapes that range from open and closed anticlines to fan folds, recumbent folds, and chevron folds, most of which are asymmetric. Although the folds are fractured and cut by subsidiary faults of small displacement, plastic deformation is dominant. The amplitude of the structures is about equal to their breadth, which ranges from a fraction of an inch to several tens of feet. They generally occur in clusters, and the axes of the individual folds show a crude alignment (Hilpert and Moench, 1960, p. 439, fig. 6). Most folds are confined to the limestone member, but some of the larger ones involve beds in the top few feet of the underlying Entrada Sandstone and basal beds of the overlying Summerville Formation where the upper gypsum-anhydrite member is missing. None of the folds is visibly truncated by bedding planes, but instead die out upward into undisturbed bedding. As the folds are almost entirely restricted to the Todilto, they are considered to be intraformational.

The gypsum-anhydrite member, which is conformable and gradational with the underlying limestone member, generally occupies the central area of Todilto deposition (Anderson and Kirkland, p. 44). It crops out north of U.S. Highway 66 in the Laguna district and along the eastern side of the San Juan Basin, but its extent to the north and west of these outcrops is only known approximately.

The Todilto is generally considered an evaporite, but the environment of deposition is uncertain and the evidence for its deposition in a marine embayment or lake basin is controversial.

The marine origin is supported largely because of the presence of fossil fish that are thought to have marine affinities, lack of chlorides in the abundant sulfate evaporites, and evidence of a marine connection between the area of Todilto deposition and the Curtis sea. Evidence for a marine connection is found in northeastern Arizona where the upper sandy member of the Entrada is missing and the formation is abnormally thin (Baker, Dane, and Reeside, 1947, p. 1668; Imlay, p. 960; Harshbarger, Repenning, and Irwin, p. 46-58).

The nonmarine origin is supported largely by the scarcity of fossils, the presence of a nonmarine ostracode (Swain, 1946), and the general gradational contact with the underlying eolian and fluvial sands of the Entrada Sandstone. Recently Anderson and Kirkland (p. 43-45) have questioned the marine affinities of the fish but found no conclusive proof either for a marine origin or for a nonmarine origin. The writer concludes, from the available information, that the Todilto probably was deposited in a shallow semiclosed basin under mixed marine and continental conditions.

The Todilto Limestone is considered to be Upper Jurassic because of its correlation with the Curtis Formation (Baker, Dane, and Reeside, 1947, p. 1668; Imlay, p. 960; Gilluly and Reeside, p. 79).

LOCAL RELATIONS

In the Grants district, only the limestone member of the Todilto crops out, but the gypsum-anhydrite member has been penetrated by drill holes about eight miles north of the outcrop (J. C. Wright, written communication, 1957). In this district, the limestone member ranges in thickness from about 5 to 30 feet, averages about 15 feet, and comprises three units which are referred to locally as the basal "platy," medial "crinkly," and upper "massive" zones.

The lower two zones, or units, are about equal in thickness and constitute about half the total thickness of the member. The "platy" and "crinkly" units consist of fine-grained, laminated, and thin-bedded limestone with thin siltstone partings and local seams of gypsum. Black dense films of carbonized material are conspicuous locally along the partings in the "crinkly" unit. The bedding in the "platy" unit generally is undisturbed, but in the "crinkly" unit it is intensely crenulated. The "massive" unit consists of more coarsely crystalline limestone with indistinct bedding and varies in thickness from place to place. In many places it contains breccia of limestone cemented by calcite, and locally the top of the unit is a breccia with fragments of limestone embedded in sand derived from the overlying Summerville Formation. The upper part of the "massive" unit also contains lenses of siltstone, indicating a gradational contact with the overlying Summerville.

In the Laguna district both the limestone and gypsum-anhydrite members are exposed. The limestone member crops out along both sides of U.S. Highway 66 and is as much as 35 feet thick in the vicinity of the Sandy mine, but to the north, where it is overlain by the gypsum-anhydrite member, it averages only about ten feet thick. It consists of two units of about equal thickness, a lower bedded unit and an upper massive unit that are lithologically and structurally similar to the "platy" and "massive" zones or units in the Ambrosia Lake area. The lower, or bedded unit, ranges in thickness from a few feet to as much as 35 feet and probably averages about ten feet. The "massive" unit is discontinuous and highly variable in thickness, being locally as much as 15 feet thick.

According to R. H. Moench (written communication, 1963), where the overlying gypsum-anhydrite member is missing, the massive limestone unit and basal sandstone beds of the Summerville Formation in many places are intimately mixed and thin layers of sandstone and siltstone are tightly folded. These relations, when considered with the general gradational nature of the Todilto–Summerville contact, suggest flowage after deposition and before consolidation of the sediments (R. H. Moench, written communication, 1963). The brecciation and mixing in the same straigraphic position in the Ambrosia Lake area, as mentioned above, suggest the same kind of flowage.

The gypsum-anhydrite member is exposed in the Laguna district mostly north of U.S. Highway 66 where it ranges in thickness from 0 to 75 feet and forms conspicuous knolls or hummocks on benches of the limestone member. This exposure is the southern end of the thick part of the member, the axis of which trends north along the east side of the San Juan Basin. At the surface, the member is almost entirely gypsum, but the hummocks in many places are capped by a thin bed of limestone (R. H. Moench, written communication, 1963). In a drill hole at the Jackpile mine, the unit is about 75 feet thick and almost entirely anhydrite. A little gypsum is present at the top, and the lower half shows irregular limestone laminae (R. H. Moench, written communication, 1963).

Many uranium deposits occur in the Todilto Limestone. All are in the limestone member and most are near the base, but some are in the middle or top or occupy the entire limestone interval. Many are not confined entirely to the limestone but extend into the underlying Entrada Sandstone or into the overlying Summerville Formation. Most of the deposits are in the Grants district but some occur in the Laguna district, as well as elsewhere in northwestern New Mexico. All the deposits are closely related to the intraformational folds in the limestone member. These folds, which are probably Late Jurassic in age, are best developed and concentrated along the southern margin of the San Juan Basin (Hilpert and Moench).

SUMMERVILLE FORMATION

NOMENCLATURE AND REGIONAL RELATIONS

The Summerville Formation was named from exposures in the northern end of the San Rafael Swell, Utah (Gilluly and Reeside, p. 80). Baker, Dane, and Reeside (1936, p. 32) extended the nomenclature to western Colorado and to the vicinity of the Four Corners. Later, Harshbarger, Repenning, and Jackson (1951, p. 40, 97, pl. 2) extended it to Fort Wingate. The terminology then was extended eastward from Fort Wingate to Laguna (Rapaport, Hadfield, and Olson, p. 27-29). For exposures in the area north of Thoreau, Smith (1954, p. 14-15), used the name *Thoreau Formation* and correlated the lower even-bedded member of this unit with the Summerville. Freeman and Hilpert (1956, p. 316, 318) used the terminology of Rapaport, Hadfield, and Olson (1952) and extended it northward to Cuchillo Arroyo on the eastern side of the San Juan Basin.

Regionally, the Summerville generally consists of a lower silty member and an upper sandy member ranging from about 50 to 330 feet in total thickness. The silty member conformably overlies the Curtis Formation in the San Rafael Swell (Gilluly and Reeside, p. 80). Southeastward from the Swell, it progressively overlies the Entrada Sandstone and Todilto Limestone (Baker, Dane, and Reeside, 1947, p. 32; Strobell; Harshbarger, Repenning, and Irwin, 1957, pl. 3). The lower silty member is a sequence of soft reddish brown mudstone and thin-bedded, silty sandstone beds that locally are gypsiferous and that in many places exhibit subaqueous slump structures (Harshbarger, Repenning, and Irwin, 1957, p. 41; Strobell). It grades upward into the upper sandy member which consists mostly of reddish brown and pale brown, fine-grained, even-bedded sandstone and some interbedded siltstone. The sandstone beds progressively thicken toward the top at the expense of the interbedded siltstone and, in the southeastern part of the area, the sandstone beds at the top individually are as much as several feet thick.

In general, the Summerville thickens northwestward and the grain size coarsens from Utah eastward and southeastward. The Summerville passes laterally into the Curtis Formation and is in part a marginal facies of the Curtis in east-central and southwestern Utah (Baker, Dane, and Reeside, 1936, p. 47). It grades into the Cow Springs Sandstone in northeastern Arizona and west-central New Mexico (Harshbarger, Repenning, and Irwin, pl. 3), and occupies the stratigraphic position of the clastic beds above the Pony Express Member of the Wanakah Formation in parts of southwestern Colorado (Read et al.).

The Summerville Formation is generally considered to represent deposits laid down in relatively quiet and shallow marine waters, but the presence of mud cracks, ripple marks, and some gypsum (Gilluly and Reeside, p. 80), poor sorting (especially in the southeast), and the lack of fossils probably indicate some subaerial deposition. Most likely the two members of the Summerville represent transgressive and regressive phases of a Curtis and Summerville sea, the lower silty member being roughly contemporaneous with the Curtis deposition, and the upper sandy member being representative of the regressive phase (Harshbarger, Repenning, and Irwin, p. 42).

LOCAL RELATIONS

In the Grants and Laguna districts, the Summerville is about 90 to 200 feet thick and is exposed in many places. It generally crops out on stripped-back benches of the Todilto Limestone as a talus-covered slope and an overlying horizontally ribbed cliff at the base of the massive cliff of Bluff Sandstone. The contacts of the Summerville are gradational and arbitrary. Freeman and Hilpert selected the base as the top of the uppermost limestone bed of the Todilto and selected the top as the top of the uppermost persistent siltstone-mudstone bed. This interpretation generally agrees with that presented by Rapaport, Hadfield, and Olson and has been followed by R. H. Moench (written communication, 1963) and E. S. Santos (oral communication, 1963).

In the Grants district, the Summerville is partly exposed in many places and completely exposed in a few places north of U.S. Highway 66 and east of State Highway 117. At Haystack Butte, about six miles north of Bluewater, it is about 160 feet thick (T. E. Mullens and L. C. Craig, written communication, 1950) and, at Red Bluff, about ten miles north of Grants, it is about 215 feet thick. At this section, a 135-foot-thick unit was measured by V. L. Freeman and the writer above a basal covered unit which was estimated to be about 80 feet thick. About 20 miles south of Grants on State Highway 117, a 15-foot-thick quartzite-pebble conglomerate is exposed at the base of the Summerville and rests on the Entrada Sandstone. The conglomerate contains fairly well rounded pebbles, some as much as three inches in diameter, imbedded in poorly sorted sand and silt.

In the Laguna district, the Summerville Formation was described by R. H. Moench (written communication, 1963) as ". . . the lower silty facies of Harshbarger and others (1957, p. 39) and the buff shale member of Kelley and Wood (1946) and Silver (1948, p. 77) . . .", which conforms with the usage of Rapaport, Hadfield, and Olson, and of Freeman and Hilpert (p. 312).

The Summerville is exposed in the district in a line of cliffs along the southern part of Mesa Gigante and in many buttes and mesas south of U.S. Highway 66. It ranges in thickness from about 100 to 180 feet. According to Silver (p. 78), it thins and coarsens southward. At Petoch Butte, it is about 140 feet thick and about 17 miles south of Petoch Butte is cut out under a pre-Dakota erosion surface. At its southern margin, the Summerville contains a basal pebble conglomerate (Silver, p. 78) which may be equivalent to the conglomerate south of Grants (*see* above). In the northern part of the district, the formation is covered and the nearest exposure north of the district is in Cuchillo Arroyo where a 60-foot-thick section is exposed at the base of the Morrison Formation (L. C. Craig, written communication, 1951; Freeman and Hilpert, p. 316).

In many places in the Laguna and Grants districts, the Summerville beds are intensely contorted, particularly in the lower part, and the formation is cut by numerous sandstone pipes. The pipes extend into the overlying Bluff Sandstone and are considered to be intraformational collapse structures that formed during the accumulation of the highest beds they cut (Hilpert and Moench).

Scattered uranium deposits occur in the Summerville Formation at the base, but few if any are of mineable grade. Most are extensions of deposits that occur in the underlying Todilto Limestone.

BLUFF SANDSTONE

NOMENCLATURE AND REGIONAL RELATIONS

The Bluff Sandstone, which conformably overlies the Summerville Formation in the Grants region was described by Gregory (1938, p. 58) from exposures at Bluff, Utah, and assigned as the basal member of the Morrison Formation in southeastern Utah. In southwestern Colorado, Goldman and Spencer (1941, p. 1750) called its equivalent the Junction Creek Sandstone Member of the Morrison, and Eckel (1949, p. 29) later raised the Junction Creek to formation rank. Read et al. redefined it as a member of the Wanakah Formation, a unit that occupies the stratigraphic position of the Summerville Formation in south-central Colorado. Craig et al. (1955, p. 133) accepted the correlation of the Junction Creek with the Bluff by Goldman and Spencer (p. 1759), but considered the Bluff as a separate formation assigned to the San Rafael Group because it tongued and intergraded with the Summerville in southeastern Utah and in bedding and lithology resembled the San Rafael Group (Craig et al., p. 133-134).

From Utah, the Bluff Sandstone extends southward into northeastern Arizona where it tongues with the Salt Wash Member of the Morrison Formation (Craig et al., p. 133) and coalesces with the Cow Springs Sandstone (Harshbarger, Repenning, and Irwin, p. 42).

In the southeastern part of the Grants region, the lithologic member names required by the Survey during wartime inactivity of the names committee were used by Kelley and Wood for the units between the Entrada Sandstone and Dakota(?) Sandstone. These were, in ascending order, the Todilto Gypsum Member, buff shale member, brown-buff sandstone member, white sandstone member, and variegated shale member of the Morrison Formation. Somewhat later, Smith (1951; 1954, p. 15) proposed a partly new set of names for the same stratigraphic interval in the Thoreau quadrangle, just west of the Ambrosia Lake area. Smith's sequence was the Thoreau Formation below, which consisted of a lower and an upper member, and the Morrison Formation above. Prior to this, the Utah terminology of Craig et al. had been followed by Rapaport, Hadfield, and Olson and, subsequently, was used by Freeman and Hilpert for rocks exposed along the southeast side of the San Juan Basin. Thus, in the Grants region, the formations between the Entrada Sandstone and Dakota Sandstone are, in ascending order, Todilto Limestone, Summerville Formation, Bluff Sandstone, and Morrison Formation. As shown in Table 3 the Bluff is the equivalent of the white sandstone and brown-buff sandstone members of the Morrison of Kelley and Wood and the upper member of the Thoreau Formation of Smith (1954).

From southeastern Utah, where it attains a thickness of about 350 feet, the Bluff Sandstone thins southward and grades into the Cow Springs Sandstone in northeastern Arizona. It is generally less than 100 feet thick in Arizona and is about 30 feet thick along the Arizona–New Mexico boundary and near Toadlena, New Mexico. From Toadlena, it grades southward into the Summerville (Harshbarger, Repenning, and Irwin, p. 40, 43). On the south side of the San Juan Basin, the Bluff generally is about 150 to about 400 feet thick and is probably thickest south of Grants and northeast of Laguna. North of the Laguna district the Bluff is absent and may grade into the Summerville and lower part of the Morrison Formation south of Cuchillo Arroyo (Freeman and Hilpert, p. 316)

Table 3. *Nomenclature of the stratigraphic units between the Entrada and Dakota Sandstones along the south side of the San Juan Basin*

Modified from Harshbarger, Repenning, and Irwin, 1957 (Fort Wingate)		C. T. Smith, 1954 (Thoreau quadrangle)		Freeman and Hilpert, 1956 (Part of northwestern New Mexico) Rapaport, Hadfield, and Olson, 1952 (South side San Juan Basin		Kelley and Wood, 1946 (Lucero uplift) Caswell Silver, 1948 (Jurassic overlap, west-central New Mexico)	
Dakota Sandstone		Dakota(?) formation		Dakota sandstone		Dakota(?) sandstone	
Morrison Formation	Brushy Basin Member	Morrison Formation	Brushy Basin shale member	Morrison formation	Brushy Basin member	Morrison formation	Variegated shale member
Morrison Formation	Westwater Canyon Member	Morrison Formation	Prewitt sandstone member	Morrison formation	Westwater Canyon member	Morrison formation	Variegated shale member
Morrison Formation	Recapture Member	Morrison Formation	Chavez member	Morrison formation	Recapture member	Morrison formation	Variegated shale member
Cow Springs Sandstone		Thoreau formation	Upper member	Bluff sandstone		Morrison formation	White sandstone member Brown-buff sandstone member
Summerville Formation		Thoreau formation	Lower member	Summerville formation		Morrison formation	Buff shale member
Todilto Limestone		Todilto limestone		Todilto limestone		Morrison formation	Todilto gypsum member
Entrada Sandstone		Entrada sandstone		Entrada sandstone		Wingate sandstone	

or may thin to a depositional edge. In the southwest part of the San Juan Basin the Bluff coalesces westward with the Cow Springs Sandstone west of Thoreau.

In most places, the Bluff intertongues and is gradational with the Summerville and the contact between the two is rather arbitrary. The contact generally is selected between the uppermost persistent siltstone and overlying thick-bedded sandstone.

The Bluff generally consists of pale red to pale brown, fine- to medium-grained, fairly well-sorted and -cemented quartz sandstone. It crops out as a massive, smooth, rounded cliff above the talus-covered slope and ribbed cliff of the Summerville. Bedding of the Bluff is marked by thick sets of large-scale, high-angle, trough-type cross beds, principally in the upper part. Some thin flat-bedded and cross-bedded sets are present, particularly in the lower part. These beds are mostly small and medium scale.

The Bluff is generally considered a product of both subaerial and eolian deposition. The lower part probably indicates some deposition in shallow water and some wind deposition, and the upper part largely wind action. Craig et al. (p. 133) considered the Bluff in Arizona to be a tongue of the Cow Springs Sandstone. Harshbarger, Repenning, and Irwin (p. 42, 44) believed the materials of both to have been derived from dunes that advanced northward from highlands in central Arizona and New Mexico, referred to as the Mogollon Highlands. The dip directions of the cross beds in the Laguna district indicate that the Bluff there was derived from the west and southwest, presumably from the same source area (R. H. Moench, written communication, 1963).

The Bluff Sandstone is generally considered to be Upper Jurassic because of its intertonguing relations with the Summerville Formation.

Local Relations

In the Grants district the Bluff sandstone is exposed in many places along the outcrop north of U.S. Highway 66. South of Highway 66 it is exposed along the escarpment east of State Highway 117. At Haystack Butte it is about 160 feet thick (T. E. Mullens and L. C. Craig, written communication, 1950) and at the Red Bluff section north of Grants it is about 270 feet thick. According to Thaden and Santos (1957, p. 73), the Bluff thickens southward from Grants, possibly to more than 300 feet.

In the Laguna district the Bluff is well exposed in cliffs on the west and south sides of Mesa Gigante and in numerous buttes and mesas south of U.S. Highway 66. The Bluff averages about 300 feet in thickness, and the thickest exposure, which is about 400 feet, is on the south side of Mesa Gigante; on Petoch Butte, south of Laguna, where the upper part has been removed by pre-Dakota erosion, the Bluff is about 220 feet thick (R. H. Moench, written communication, 1963). Southward from Petoch Butte it is progressively cut out under the pre-Dakota erosion surface and about 25 miles south of Laguna has been entirely removed (Silver).

Moench has found that in the eastern part of the district, the lower part of the Bluff is light reddish brown and the upper part is light yellowish gray, whereas in the western part the entire formation is light yellow gray or very pale orange. He attributes the lighter colors in the lower part of the Bluff in the western part to alteration effects of numerous diabase dikes and sills. Because of this difference, identification of the Bluff across the Laguna district cannot be based solely on color (R. H. Moench, written communication, 1963).

The Bluff Sandstone contains no known uranium deposits.

MORRISON FORMATION

NOMENCLATURE AND REGIONAL RELATIONS

Cross (1894, p. 2) applied the name *Morrison Formation* to exposures near Morrison, Colorado; since then, the Morrison has been recognized throughout much of the western interior of the United States, including Colorado, eastern Utah, part of northeastern Arizona, and northwestern New Mexico. The age, stratigraphic relations, and definition of its members, however, have been subjected to much work and discussion, which has led to a voluminous literature. For a general background, the reader is referred to Cross, Emmons, Cross, and Eldridge (1896); Lupton (1914); Gilluly and Reeside; Baker, Dane, and Reeside (1936); Gregory (1938); Stokes (1944); Waldschmidt and LeRoy (1944); Harshbarger, Repenning; and Jackson; Harshbarger, Repenning, and Irwin; and Craig et al.

The Morrison is generally considered to be Late Jurassic (Imlay, p. 953-960), although the upper part in some places might be younger.

Craig et al., in a summary report based on extensive stratigraphic studies in the Colorado Plateau, gave a rather detailed discussion of the stratigraphic relations and over-all distribution. They defined the base of the Morrison in the Colorado Plateau region as the base of the terrestrial, fluvial Jurassic deposits overlying beds of the marine and marginal marine San Rafael Group, and outlined the Morrison as a crude, lenslike mass that extends from a wedge-edge in northeastern Arizona northeastward across Utah, northwestern New Mexico, and western Colorado. Throughout this region, the Morrison is generally conformable on the San Rafael Group, ranges in thickness from 300 to 900 feet and averages about 500 feet.

The Morrison is mostly a sequence of interbedded sandstone, claystone, or mudstone, some thin-bedded limestone, and some conglomerate. The sandstone units range from a foot or so to more than 100 feet in thickness, are arkosic, contain much interstitial clay or mudstone and locally carbonized plant fragments and fossil logs. The sandstone is commonly cross-stratified and has conspicuous cut-and-fill structures in many places. The upper part of the Morrison is mostly claystone or siltstone and some sandstone. The claystone contains much bentonitic material which tends to swell when wet.

The Morrison generally grades from conglomeratic sandstones in the southwestern part of the region to finer material, mostly mudstone, in the northeastern part. It wedges out in northeastern Arizona and west-central New Mexico partly as a result of pre-Dakota erosion (Craig et al.).

Regionally, the Morrison consists of four members which are, in ascending order, the Salt Wash, Recapture, Westwater Canyon, and Brushy Basin. Each of the lower three constitutes a fanlike lens that generally grades from conglomeratic sandstone along the southwestern margin to mudstone along the northeastern recognizable limit of the member. The Brushy Basin, the uppermost member, is largely a lenticular unit of claystone (much of it bentonitic), some thin beds of limestone, and some silt and sand (Craig et al., p. 138-156).

Studies of the lithology and sedimentary structures of the Morrison by Craig et al. indicate that the sediments were largely derived from a landmass in west-central Arizona and west-central New Mexico and were deposited by an aggrading system of northeastward-flowing streams. The sediments of the Brushy Basin Member were probably deposited in a mixed lacustrine and fluvial environment in which the fluvial material probably came largely from the Mogollon Highland to the south (Harshbarger, Repenning, and Irwin, p. 55). The bentonitic claystone is interpreted to be a derivative of volcanic ash (Craig et al., p. 160).

All four members of the Morrison are present in northwestern New Mexico, but in the southern part of the San Juan Basin, the Salt Wash is absent and the other three members have been referred to by different names (Kelley and Wood; Silver; Smith, 1954). Freeman and Hilpert used the terminology of Craig et al., and extended it across the southern side of the San Juan Basin. Others (Granger et al., 1961; Schlee and Moench, 1961; Granger, 1962) have followed the terminology generally. Thus, as shown in Table 3, the Recapture, Westwater Canyon, and Brushy Basin members are the correlatives, respectively, of the Chavez Member, Prewitt Sandstone Member, and the Brushy Basin Shale Member of the Morrison Formation of Smith (1954); they are collectively the equivalent of the variegated shale member of the Morrison Formation of Kelley and Wood and Silver.

LOCAL RELATIONS

In the Grants district, the Morrison is widely exposed north of U.S. Highway 66 and is partly exposed immediately south of Highway 66 and east of State Highway 117. In the Laguna district, it is exposed in a belt extending northeasterly across the district and is best exposed for several miles north from Laguna. In general, the Morrison rests conformably on the Bluff Sandstone, although locally the surface contains shallow scours. The Dakota Sandstone overlies the Morrison unconformably, but generally without marked angularity. However, in the Grants district, about two miles south of U.S. Highway 66 on State Highway 117, the Morrison is cut out under the pre-Dakota erosion surface and, southward from the vicinity of the Jackpile mine in the Laguna district, the pre-Dakota erosion surface successively truncates older beds; at Petoch Butte the entire Morrison has been removed (Silver). The angular relations of the beds on each side of the unconformity can be observed best immediately southwest of the Jackpile mine where the Dakota Sandstone rests on truncated broad folds in the Morrison.

Throughout most of the Grants region, the Morrison, comprising the Recapture, Westwater Canyon, and Brushy Basin members, is 0 to about 600 feet thick, averaging about 450 feet. In the Grants district, each member has an average thickness of 150 feet, but in the Laguna district the Recapture and

Westwater Canyon members are thinner and somewhat discontinuous and the Brushy Basin is thicker. Also in the Laguna district, a prominent sandstone unit, informally referred to as the Jackpile sandstone of economic usage, is present in the upper part of the Brushy Basin. The stratigraphic relations between these units in the two districts are shown in Figure 2.

The Recapture Member is conformable on the Bluff Sandstone. The contact generally is even and sharp and is marked by changes in lithology, bedding structures, and colors. In places, the two units grade and intertongue, and in some places the Recapture rests on scoured or channeled surfaces that have a foot or so of local relief. The Recapture in the Grants district generally ranges in thickness from about 50 to more than 200 feet and has an average thickness of about 150 feet. In the Laguna district, it is thinner and generally ranges in thickness from about 25 to 50 feet, although locally it is as much as 100 feet thick. In Cuchillo Arroyo north of the district, it is about 275 feet thick (Freeman and Hilpert, p. 316, 325).

The Recapture consists mostly of distinctive alternating grayish red and gray beds of sandstone, siltstone, mudstone, and a few thin beds of gray limestone. The beds generally range from a foot or so to several feet thick and some beds of sandstone are as much as ten feet or more thick. The sandstone is soft, clayey, poorly sorted, and mostly fine- to medium-grained. Locally, it contains small lenses of granules and small pebbles and concentrations of carbonized plant debris. It is commonly ripple-laminated and thin-bedded. Cross beds are not conspicuous and where present are small to medium-scale and planar type.

The Recapture contains a few uranium deposits, but they are generally small and of low grade.

The Westwater Canyon generally overlies the Recapture throughout the area. From place to place, the contact is a scour surface or is gradational or the members intertongue. The Westwater Canyon is thickest in the Ambrosia Lake area where it ranges from less than 50 to nearly 300 feet in thickness and has an average thickness of about 150 feet. In the Laguna district, it ranges in thickness from about ten to more than 100 feet, but generally has an average thickness of less than 50 feet; it is absent locally on the south end of Mesa Gigante and, in the southwestern part of the district, locally fills scours that cut through the Recapture and into the Bluff Sandstone (R. H. Moench, written communication, 1963). North of the Laguna district at Cuchillo Arroyo, it is about 170 feet thick (Freeman and Hilpert, p. 316, 324).

The Westwater Canyon is mostly a light yellow-brown to gray, fine- to coarse-grained, poorly sorted, cross-bedded sandstone. It is arkosic and contains some small lenses of granules and small pebbles and some thin seams or beds of gray mudstone and siltstone. Grains and granules of pink feldspar and flecks of white kaolin are conspicuous in hand specimens. Fragments of silicified logs are present locally, but most are small. The cross-bedding is generally small- to medium-scale trough type. The cross beds dip southeastward in the lower part and northeastward in the upper part in the Ambrosia Lake area (E. S. Santos, written communication, 1963) and generally northeastward in the Laguna district (R. H. Moench, written communication, 1963). Pipelike collapse structures similar to those in the Bluff and Summerville occur in a number of places in the Westwater Canyon Member in the Ambrosia Lake area.

The Westwater Canyon contains many large uranium deposits in the Ambrosia Lake area, in the Smith Lake area north of Thoreau, and northeast of Gallup. These deposits are closely associated with fine-grained carbonaceous matter that coats the sand grains and fills pore spaces within the sandstone.

The Brushy Basin conformably overlies the Westwater Canyon Member and is overlain unconformably by the Dakota Sandstone. The contact with the Westwater Canyon is generally gradational and the two members intertongue extensively; so the selection of the contact is quite arbitrary. The writer defines the contact as the base of the lowermost persistent mudstone or claystone unit. In the Ambrosia Lake–Laguna area, the Brushy Basin is about 20 to more than 300 feet thick. It generally thins westward and is cut out northeast of Gallup under the pre-Dakota unconformity. It thickens eastward from the Grants district into the Laguna district (fig. 2) and, as indicated by drill data, apparently northward as well.

The Brushy Basin in the general area is chiefly greenish gray mudstone but contains much interbedded sandstone and a few thin beds of gray limestone. The sandstone beds are similar in color and lithology to the Westwater Canyon, range from a foot or so to several tens of feet in thickness, and some of them extend for several miles. Also, sandstone beds at the top of the Westwater Canyon intertongue with the lower part of the Brushy Basin. One of these in the Ambrosia Lake district extends eastward or northeastward back from the outcrop and is referred to as the Poison Canyon sandstone of economic usage (Hilpert and Freeman). Its eastward and northward extent is uncertain. In the Laguna district, a relatively thick and extensive sandstone unit at the top of the Brushy Basin immediately under the Dakota Sandstone is referred to as the Jackpile sandstone of economic usage (Hilpert and Freeman). It is best exposed at the Jackpile mine where it contains the large Jackpile deposit and other nearby deposits. The Jackpile sandstone has been described in some detail by Schlee and Moench, from whose report it will be summarized here.

The Jackpile sandstone is a northeast-trending lens as much as 13 miles wide, more than 33 miles long, and locally 200 feet thick. It broadens northward and divides into two smaller trough-shaped fingers. It is an erosional remnant of the original mass and, before it was beveled by pre-Dakota erosion, may have extended over a much more extensive area. It apparently occupies a pre-Dakota structural depression, as indicated by the angular unconformity at the base of the Dakota, intertonguing of the sandstone at the base of the Jackpile sandstone with the Brushy Basin mudstone, and the apparent thickening of the part of the Morrison Formation that underlies the Jackpile sandstone toward the center of the sandstone lens.

The Jackpile sandstone is similar to the Westwater Canyon, except for a higher content of kaolin, color differences, and other evidences of slight alteration: It is generally chalky white in the upper part and yellow-gray in the lower part. The white color results partly from the kaolin content and partly from removal of pigmenting colors. The kaolin is an alteration product of feldspar minerals caused by weathering during the interval between deposition of the Morrison and Dakota sediments (Leopold, 1943; Schlee and Moench; Granger). The cross beds in the Jackpile sandstone dip gen-

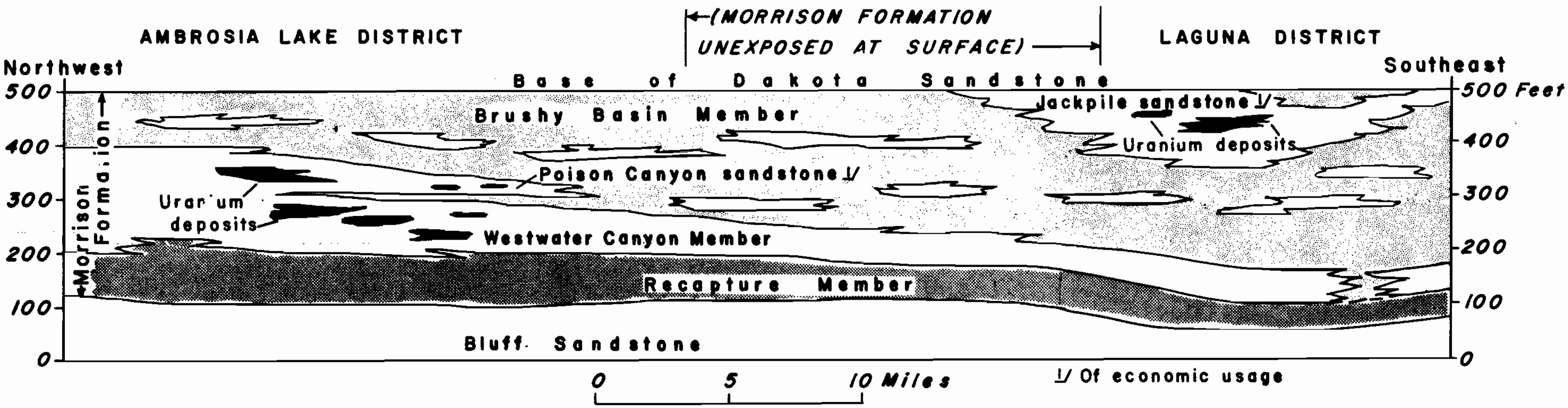

Figure 2

GENERALIZED GEOLOGIC SECTION SHOWING THE STRATIGRAPHIC RELATIONS OF THE MORRISON FORMATION BETWEEN AMBROSIA LAKE AND LAGUNA erally northeastward, indicating a northeastward direction of transport which is parallel to the axis of the sandstone unit.

Other sandstone units in the Brushy Basin occur immediately under the Dakota Sandstone west of the Ambrosia Lake area and north of the Laguna district and show bleaching (probably kaolinized) in the upper part similar to the Jackpile sandstone. One of these units crops out about six miles north of Prewitt and contains the Francis and Evelyn uranium deposits. Another unit crops out on the east side of the San Juan Basin (Swift, 1956).

Most, and by far the largest, of the uranium deposits in the Ambrosia Lake–Laguna area are in the Brushy Basin and Westwater Canyon members of the Morrison Formation.

The Westwater Canyon contains many large deposits such as the Dysart and Cliffside and others to the west. Sandstone lenses in the Brushy Basin also contain many deposits. The largest ones are in the Jackpile sandstone in the Laguna district, including the large Jackpile deposit. Also, the pipelike Woodrow deposit in the Laguna district is in the interval that extends from the lower part of the Jackpile sandstone into the underlying mudstone. In the Ambrosia Lake area, deposits in sandstone lenses in the Brushy Basin are generally smaller than those in the Westwater Canyon.

The Recapture Member contains relatively few deposits; most are not of mineable size and grade; an exception is the Chaves deposit, which has yielded some ore.

DAKOTA SANDSTONE

NOMENCLATURE AND REGIONAL RELATIONS

The Dakota Sandstone of Early and Late Cretaceous age unconformably overlies the Morrison Formation and older strata and is overlain conformably by the marine Mancos Shale of Late Cretaceous age throughout the Grants region. The name *Dakota Group* was applied originally by Meek and Hayden (1862) to rocks of Late Cretaceous age near Dakota, Nebraska. Since then the name, or qualifications of it such as Dakota(?) Formation, Dakota(?) Sandstone, and Dakota Sandstone, has been extended over large areas in the western States to rocks in approximately the same stratigraphic position. In northwestern New Mexico, the name has been applied generally to the lowermost strata of Cretaceous age that unconformably rest on the Jurassic and older strata.

In the south part of the San Juan Basin, the Dakota generally is about 75 to 100 feet thick, except in the Laguna district where it is locally less than five feet thick (Dane and Bachman, 1957, p. 96; Young and Ealy, 1956; Dane, 1960, p. 51; Smith, 1954, p. 18; R. H. Moench, written communication, 1963). It consists mostly of tan to gray quartz sandstone, dark gray carbonaceous shale, and local lenses of conglomerate and impure coal. The sandstone ranges from fine- to coarse-grained but generally is medium-grained, is clean, and contains numerous small molds of carbonized plant fragments. The sand grains are fairly well rounded and cemented by silica. The Dakota from place to place forms one or more sandstone units, which are generally separated by thin beds of carbonaceous shale and locally by coal lenses. The sandstone units are generally cross-bedded in the lower part and even-bedded in the upper part. Most of the carbonaceous shale is at the base. Conglomerate lenses occur locally and mostly at the base of the formation where they occupy scours in the top of the Morrison Formation. Some scours are as much as 25 feet deep and are characteristically filled by a mixture of quartz sand, quartz pebbles, and scattered pieces of fossil plant debris.

The Dakota crops out in most places as prominent benches and in vertical blocky cliffs. The cliff faces are commonly iron-stained and hence readily recognized above the light-colored sandstone and gray mudstone of the Morrison Formation.

The Dakota Sandstone in northwestern New Mexico was assigned a Late Cretaceous age by Cobban and Reeside (1952, chart 10b). Fossil data from the basal part of the Dakota near Acoma confirm that it is not older than Late Cretaceous (Dane, 1959, p. 90). Dane and Bachman (p. 97, 98) indicated that in the Gallup area, however, part of the Dakota may be of Early Cretaceous age.

The Dakota Sandstone is generally considered to be an accumulation of near-shore continental deposits that were laid down by streams and in swamps during and following a long period of erosion and weathering which must have lasted at least throughout most of Early Cretaceous time. The cross-bedded sandstone, conglomerate-filled channels, and interbedded carbonaceous shale and coal are indicative of such conditions. Dane and Bachman (p. 97) interpreted the Dakota in the Gallup area as a transgressive deposit that is partly a fluvial, partly a lagoonal, and partly an off-shore sandy marine unit and interpreted the advance of the sea as originating probably from the east and south, and representing the last phase of Dakota deposition. Moench (written communication, 1963) believes similar conditions prevailed in the Laguna district, and he interprets the sands and gravels in the lower part of the Dakota as deposits from streams that probably flowed from the west.

LOCAL RELATIONS

In the Ambrosia Lake area, the Dakota crops out in low cliffs, on mesa tops, and in prominent benches north of U.S. Highway 66 and east of State Highway 117. In many places, it consists of an upper sandstone unit and a lower, somewhat thinner, carbonaceous shale unit. It generally is about 50 to 125 feet thick and averages about 80 feet thick. In the Laguna district, it likewise crops out in low cliffs, on mesa tops, and in prominent benches throughout the area and ranges from less than 5 feet to more than 100 feet thick; in the northeastern part of the district, sandstone is absent locally and the formation consists entirely of black shale (R. H. Moench, written communication). The average thickness in the Laguna district is probably less than 50 feet.

A few uranium deposits occur in the Dakota Sandstone, mostly near the base in channel scours, or closely associated with carbonized plant material. A few in the Ambrosia Lake area, such as the Silver Spur, have yielded ore.

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